Synthetic Aperture Sonar On AUV

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Abstract– Synthetic aperture sonars (SAS) and autonomous underwater vehicle (AUV) are two of the most exciting technologies under development by the underwater research and development community. Integration of these technologies promises to produce underwater acoustic imaging systems of tremendous capability and versatility. Currently, several efforts, mostly motivated by military applications, are under way to achieve the realization of these systems. This paper describes one such effort, in which the Coastal Systems Station (CSS) SAS system has been integrated with the Bluefin Reliant AUV. Included in this paper are descriptions of the CSS SAS and Bluefin AUV technology and hardware and of the data processing methods. Also presented are the preliminary results obtained during the first system tests carried out at CSS, Panama City, Florida in March 2003.

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I. INTRODUCTION

The need to perform dangerous commercial and military underwater sea operations without placing humans at risk is the main motivation for the proliferation of autonomous underwater vehicle (AUV) systems. Presently, from a military perspective, there is probably not a more important and dangerous task than sea mine countermeasures (MCM). Sea mines in terms of stealth, availability, cost-effectiveness and ease of deployment are perhaps the most attractive weapons available to any country determined to cause damage to naval assets during terrorist and/or military confrontations. Once sea mines are deployed, they become a lethal threat for both military and commercial ships until they are found and neutralized. A single low cost mine can sink or cause severe damage to a ship and, more devastating, inflict irreplaceable human casualties.

A. Mines

Mines are typically categorized by their position in the water column, i.e., either floating, moored or bottom mines. Floating and moored mines are typically used in deep water (DW) and shallow water (SW) zones; water depths greater than 200 feet and between 200 and 40 feet, respectively. Bottom mines are deployed where they are in closer proximity to the intended targets, typically in the very shallow water (VSW) and surf zone (SZ); where water depths range between 40 and 10 feet and 10 feet in, respectively. Effective MCM becomes progressively more difficult as the water depth decreases. In shallower waters, environmental conditions are more dynamic and harsh, and larger amounts of clutter or non-mine bottom objects (NOMBOs) exist. Additionally, in these zones, bottom mines tend to bury either by the initial impact, scouring and/or sedimentation.

Modern underwater sea mines are becoming increasingly complex with multi purpose capabilities. They have sophisticated target sensing and firing mechanisms, which provide them with a wide target engagement zone and a short time of attack. These combine to practically deprive the target of the opportunity to take countermeasures or perform an evasive maneuver.

B. "MCM 101"

In DW and SW regions, MCM is done predominantly by surface ships and/or helicopters towing mechanical minesweeping, influence minesweeping and minehunting systems. Mechanical minesweeping systems use cable cutters to cut the cables of moored mines, so that they float to the surface for neutralization by gunfire. Influence minesweeping systems use acoustic and/or magnetic devices to confuse the mine firing mechanism, "tricking" them into detonation. Minehunting systems use mine hunting sonar, optical and magnetometer sensors to search for mines. These systems, under most conditions, are capable of detecting and classifying mines, which are then marked and prosecuted for identification by either divers or remotely operated UUVs equipped with underwater video hardware. Once a mine is positively identified, it is neutralized with explosives set on or near the mine by divers.

From the VSW in towards the shoreline or surf zone (SZ), where MCM towing vessels cannot venture, remotely operated UUVs, mammals, and divers are used to find and neutralize mines (even buried ones!). In this region, more destructive methods like explosive line charges and intense air strikes are also used.

All these MCM methods are non-covert, tremendously slow and extremely dangerous. Ships put themselves at risk by navigating in mine-infested waters, helicopters by flying low and slow over the water (becoming an easy target for enemy forces), and divers are subject to risks associated with handling explosives, mines and deep water diving. These factors along with the desire to remove humans from direct risks, the increased sophistication of new mines, and the goal of providing surface ships and submarines with organic, and ultimately their own level of, MCM capability have motivated the development of AUV systems for MCM.

Several programs are underway in various NATO countries to develop AUV-based MCM systems and the various enabling technologies needed to improve the capabilities of AUVs, such as: energy sources, precise

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navigation, underwater communications, sensors, and autonomy. Autonomy is without doubt the most challenging aspect. AUVs will have to avoid obstacles and even adapt their mission as a function of the environment by assessing and evaluating incoming information from a variety of sensors (all without direct human intervention!).

The diversity of environmental conditions found through the various water depth zones (DW, SW, VSW and SZ) point towards the need for different AUV platforms and sensor packages. In addition, it raises the difficult question of whether AUV-based MCM should be tackled by a single type of AUV capable of performing detection, classification, identification and marking (DCI&M), or tackled by multiple less complex (and therefore smaller) AUVs dedicated to provide a subset of the functionalities, i.e., some AUVs do D&C while others do I&M.

In any event, for all this to happen, more capable sonar sensors are required. Sonar sensors of high resolution, high area coverage rate and small physical presence are desirable to improve the overall performance of the AUV system. In minehunting operations reducing the number of false targets is essential in improving the efficiency of MCM operations (less time and resources needed to prosecute non mines). This can only be achieved with a high performance sonar system and associated automatic DC&I algorithms.

C. Minehunting Side Looking Sonars

The type of sonar most used for minehunting is the side looking sonar (SLS). SLS systems use line arrays mounted on the sides of the underwater vehicle (UV), looking to the sides perpendicular to the direction of travel, hence their name. This configuration is advantageous because the sides are the longest dimension on an UV, allowing for longer transmitter and receiver physical array(s), which for a given operational wavelength translates to a finer along-track resolution and higher area coverage rate capability.

Modern high-performance minehunting SLS are multi-beam conventional or real aperture designs. They combine the use of a long physical array, compared to the operational wavelength (typically hundreds to thousands wavelengths long) and short operational wavelengths (high frequencies) to achieve the resolutions required for D&C. In real aperture SLS designs, for a fixed array length, resolution improves as the operational frequency is increased. Unfortunately, as the operational frequency is increased the maximum range is reduced. This is because absorption losses in the medium (sea water) increase with increased frequency. To compensate for this, real aperture SLS systems are towed at high speeds to achieve high area coverage rates (ACR). These SLS systems have been shown to deliver significant detection and classification capabilities against large mines in benign deep-water environments to ranges in the order of 100 to 200 meters. In shallow waters they are less effective because they do not have capabilities required to tackle the higher density of NOMBOs and buried mines found in those zones. These types of SLS designs also tend to be inefficient for most AUV applications/platforms. AUV systems are typically designed to have a small physical presence and to operate at relatively slow speeds (around 3 knots) to lengthen endurance (propulsion power is proportional to the velocity cubed). Under those conditions, a high performance real aperture SLS design would exhibit a low ACR.

A more efficient SLS design for AUV platforms would be one based on synthetic aperture (SA) technology. SA technology has matured tremendously over the last decade due, for the most part, to the tremendous advances in digital electronics (memory, processors, etc.). SA technology possesses characteristics that are advantageous for AUV platforms. SA technology uses the forward motion of a small physical array to synthesize a much larger array, thus resulting in much finer along-track resolutions and higher signal to noise ratios than that of the actual physical array. Another benefit of a SA technology is that by virtue of modifying the SA integration time (aperture length) the along-track resolution can be made constant independently of frequency and range. As a consequence lower operating frequencies (lower absorption) can be used in a SAS to increase range, effectively increasing the ACR, without compromising performance (resolution and D&C capability). Another advantage of SAS over real aperture is that SAS systems have a wider field of view, hence capturing a larger horizontal angular response from the target. This reduces the likelihood of missing a target because of a poor viewing angle (target at a low reflectivity angle). The factor that would most influence the level of performance of SAS systems is undesired platform motions. As mentioned earlier, the main idea behind the SA technique is to synthesize a large aperture array by exploiting the forward motion of the platform. This aperture is created by properly combining the stave responses produced by pinging (transmitting) and receiving from a sequence of locations along the direction of travel. The position of these locations is critical and is determined by the motion of the platform and the ping rate. The ideal path to synthesize the aperture is a straight line traveled at a constant velocity. Any deviation of either will produce errors that will degrade the beam pattern of the SA. In practice these deviations exist and must be measured and compensated for by the SA beamformer. They are typically measured by carrying a separate motion measurement package (MMP) along with the sonar and/or by estimating them from the sonar data itself. A motion estimation method that is used by several experimental SAS systems is the displaced phase center (DPC) technique. This technique measures differences in the time of arrival of sea bottom backscatter between overlapping phase centers to infer motion between pings. This technique has been shown to work well at ranges in the order of 3000 to 5000 wavelengths and at range-to-water depth ratios between 1 and 3.

MCM capabilities can be improved further by using large bandwidths. Increasing operational bandwidth of the sonar results in better range resolution, reverberation suppression and additional information about the environment and targets. All these combine to improve the overall sonar sensor performance.

II. RELIANT/SAS21 SYSTEM

The RELIANT/SAS21 system is the first experimental MCM system that exploits the use of SAS and AUV technology. The system, shown in Figure 1, is programmed to perform specific missions, either before deployment or at sea via RF modem communications. Defined within the mission are the intended behaviors, i.e., tracks, speed, altitude, sonar control, etc. Once the AUV is commanded to start the mission, the onboard navigation computer uses the data from the navigation system to make any necessary attitude adjustments to maintain the desired course. The system is approximately 3 meters in length by 0.53 meters (21-inch) in diameter and weights approximately 1100 pounds. The system operates at up to 200 meters in depth and at a typical speed of 3 knots. The following subsections provide a brief description of the AUV and SAS.

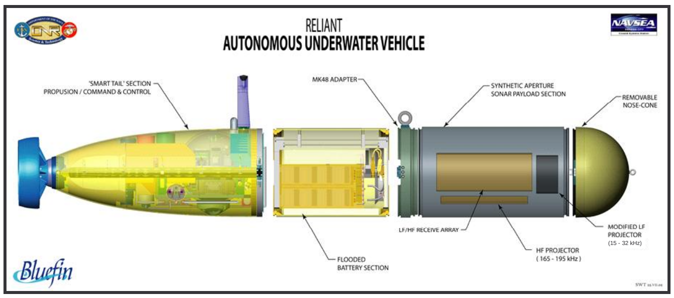

Figure 1. REALIANT/SAS21 System

A. RELIANT AUV

RELIANT is a 21-inch diameter AUV developed by BlueFin Robotics. RELIANT consists of various subsystems and sensors for communications (RF and acoustic modems), positioning (Global Positioning System (GPS)), navigation (RD Instruments 300 kHz Workhorse Navigator Doppler Velocity Log (DVL) and Litton LN250 Inertial Navigation System (INS)) and power (Lithium Polymer battery packs.) All subsystems, except for the batteries, are packaged in pressure vessels inside the free flooded fairings that form the tailcone. The hull shape and material were selected to facilitate handling, performance and integration with sensor payloads. Currently the battery section (fore of the tailcone) contains three 2 kWh packs (nominal 30Vdc), two of which are used to power the SAS21 sensor. These battery packs are designed for use in underwater vehicles, with a solid encapsulated section containing the lithium polymer cells and a small oil-filled section housing the electronics.

While RELIANT is on the surface GPS information is used for positioning and INS alignment. When submerged, coupled information from the Litton LN250 INS and RDI DVL units are used for precise navigation. RELIANT uses an actuated ducted thruster design for propulsion, heading and attitude adjustments. In addition, the ducted thruster design provides the roll compensation the vehicle requires without needing wings and fins.

RELIANT has several safety features that include mission timers, bottom avoidance, an acoustic abort system and an acoustic tracking system.

Mission planning, control commands and status monitoring of RELIANT are done with the topside control computer (a Pentium class computer) and associated software via shore cable or RF modem communications.

B. SAS21

SAS21 is the new name given to the Coastal Systems Station (CSS) low frequency high frequency synthetic aperture sonar (LF/HF SAS) sensor package after its data acquisition, recording, control and transmit electronics were upgraded by the Applied Research Laboratory/Penn State University (ARL/PSU) with more modern, compact, versatile and power efficient designs. In addition, during the upgrade process, the LF bandwidth was increased by 7kHz and capabilities were developed to allow operation from either towed or autonomous underwater vehicles. In its current configuration, SAS21 is a dual sided (port/starboard looking) sonar operating simultaneously over two frequency bands (15kHz-32kHz and 165kH-195kHz) with a capacity to acquire/store 160Gbytes of raw data (80 minutes of raw data recording). The transmit waveform and power of SAS21 are independently programmable for both the LF and HF bands. The LF can produce 7.62 cm x 7.62 cm (3” x 3”) resolution imagery of proud and even buried targets, and the HF can produce 2.54 cm x 2.54 cm (1” x 1”) resolution imagery of proud targets. The simultaneous dual frequency operation provides the system with detection and classification (DC) capabilities for volume, proud, and buried targets in a single pass, even in the harsh environments found in the shallow water (SW) and very shallow water (VSW) regimes. The SAS21 package, shown in Figure 1, is contained in a 0.53 m (21”) diameter shell section less than 1 meter in length.

The primary motion estimation and compensation methodology used in SAS21 is a two-element ping-to-ping overlap DPC approach. SAS21 also uses velocity estimates from a Doppler Velocity Log (DVL) instrument to adapt the ping rate as a function of speed, thus maintaining a constant translation between ping intervals. The capabilities of this approach and the dual frequency SAS design have been well documented [1-6] and demonstrated during various tests and Navy fleet exercises.

Onboard the RELIANT AUV, the main vehicle computer communicates with the control computer of SAS21 via a network connection to control and monitor the status of SAS21. In this configuration, the SAS21 control computer receives navigation and DVL velocity estimates from RELIANT.

C. Initial RELIANT/SAS21 System Test Results

The initial RELIANT/SAS21 system performance tests were carried out in St. Andrews Bay, Panama City, Florida during the January through April 2003 time period. Figure 2 shows the system during one of the launching evolutions.

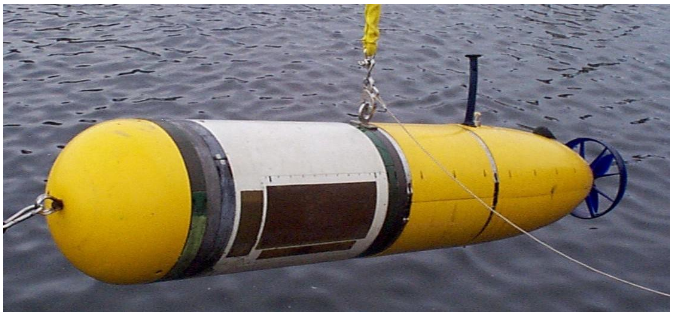

Figure 2. REALIANT/SAS21 System

The main objective of the tests was to demonstrate autonomous MCM capability in the VSW zone. With that purpose, missions were executed emulating typical very shallow water (at around 8 meters water depth) MCM survey missions, i.e., performing specific maneuvers/tracks at different speeds, depths and ranges against various targets in different areas of the bay. Figures 3, 4 and 5 show typical images generated by SAS21, where the y-axis and x-axis are the along-track and range direction, respectively. Both are in meters, with the y-axis referenced to the beginning of the track. Figure 3 shows a cylindrical target in a fairly smooth bottom. Figure 4 shows another cylindrical target that was dragged, most likely caught in the nets of by a shrimp boat (as evident by the trawling marks.) Figure 5 shows typical features of the sea bottom, which would increase the difficulty of detecting and classifying mines using a sonar of inferior capability.

The images were generated using the well-known wavenumber domain beamformer, after motion compensating the sonar data via the DPC technique (using the SAS21 DPC element pairs.) A companion OCEANS 2003 paper entitled "Motion Compensation of AUV-Based Synthetic Aperture Sonar" describes the use of additional information from the INS and DVL units to improve motion compensation and thus the image quality.

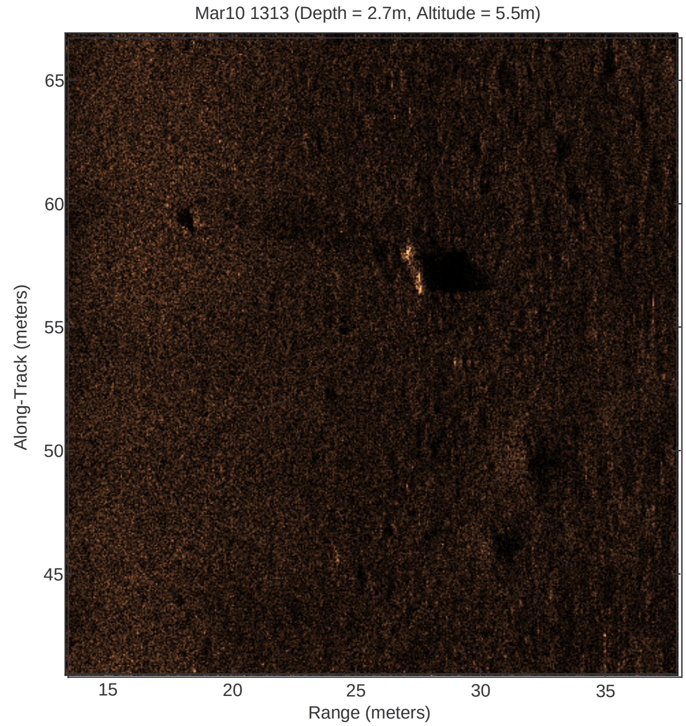

Figure 3. HFSAS Image of Cylindrical Target

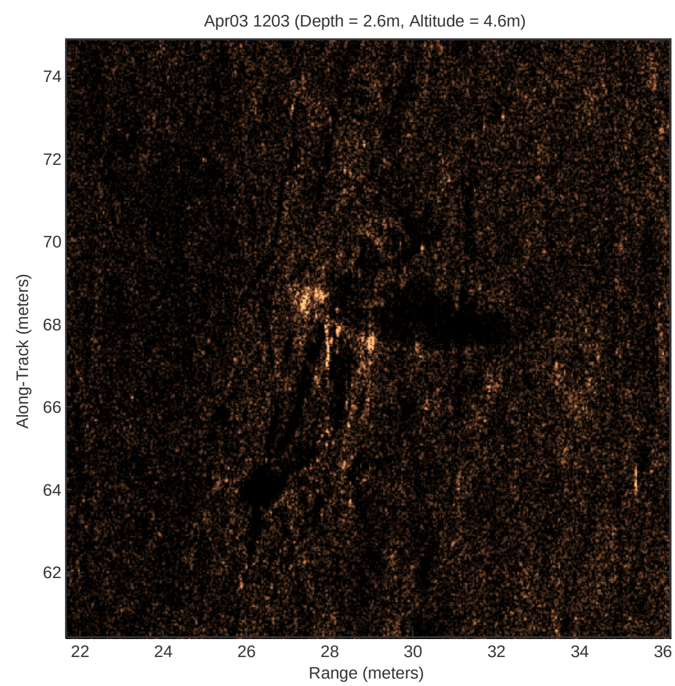

Figure 4. HFSAS Image of Cylindrical Target

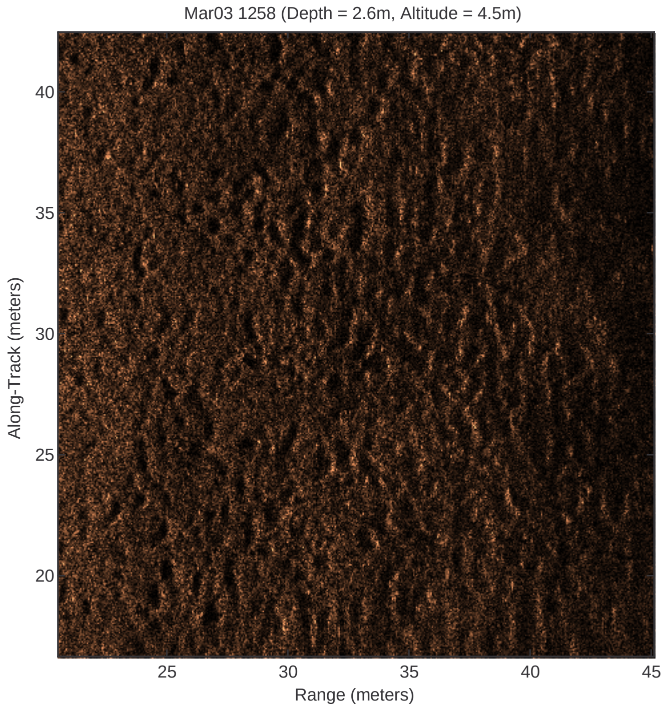

Figure 5. HFSAS Image of Sea Bottom Features

VII. Conclusion

MCM is on the verge of a revolution. The future will bring progressively more capable AUV MCM systems thanks to advances in the fields of robotics, autonomy, materials, underwater navigation and communications, energy storage, electronics and sensor technology, like SAS. These systems will provide surface ships and submarines with their own resources for mine avoidance and neutralization at all depths and without having to place humans at risk.

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